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A HORIZONTAL HIGH VACUUM ELECTRICAL RESISTANCE FURNACE[1]

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Abstract

A high temperature vacuum furnace is described which has been in almost continuous use during the past four years in the production from powders of sintered compacts of titanium and titanium alloys. The success which has attended its use has suggested that information regarding its design and operation might be of value to others working in the field of vacuum metallurgy. Although vacuum furnaces are technologically applicable to industry, economically they are applied only where other alternatives do not present themselves. This is mainly due to the present high cost of installation and operation. The main contributory factor to high cost, particularly with large furnaces, is degassing refractories. The problem is to reduce the amount of refractories which degas to a minimum. Two methods of doing this are discussed—one employs heat resistant alloy or metal within an insulated heated chamber—the other employs a refractory heater surrounded by an insulated radiation shield to protect the inner side of the insulated furnace wall. The furnace described herein was built to the latter design.

Introduction

Recent developments in metallurgy have called for furnaces in which a wide variety of metallurgical operations can be carried out *in vacuo*. The experience gained in the construction and use of laboratory equipment has, of course, been used in the design and development of commercial vacuum furnaces. As a result, for example, induction furnaces capable of melting and pouring large masses of metal *in vacuo* have been constructed and used (4, 9, 10, 11). However, the development of large vacuum units for the treatment of metals at temperatures below their melting points is relatively immature. It is the purpose of this paper to describe a laboratory furnace designed for the production of sintered compacts of titanium and titanium alloys. This furnace has been in continuous use for the past three years. It embodies features the description of which, it is hoped, may be of value to others interested in vacuum metallurgy, even on a larger scale.

Design Considerations

It would be illogical for metallurgists to employ vacuum furnaces in place of controlled atmosphere furnaces in the fabrication or treatment of most

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metals and alloys. In dealing with such highly reactive metals as chromium and titanium, however, vacuum furnaces have been found of value. But the use of such furnaces, even though they may have been designed to fabricate and treat reactive metals need not be confined to this service. Vacuum furnaces can be used for other metals as well.

Objections which might be raised to the installation of vacuum equipment are (1) the relatively high initial and operating costs of such equipment, (2) the difficulties of preventing and locating leaks in vacuum systems, and (3) the inconvenience that results from the rather frequent need to cool work *in vacuo* before removing it from the furnace. So far this last objection has restricted the application of vacuum furnaces to batch and semibatch processes and to specialized and experimental work involving a small production.

The widely held impression that high vacuums (10^{-4} to 10^{-5} mm. of mercury) are difficult to achieve and maintain is unwarranted in the light of recent developments in vacuum engineering. The gaseous diffusion plant for the separation of U^{235} and the vacuum distillation plant for the recovery of magnesium by the Pidgeon process are but two examples of large scale installations operating successfully today (5).

As to the first of the objections referred to above, development costs constitute an appreciable item of expense and must generally be added to the first cost of new furnaces. Operating expenses at present assume large proportions because skilled technicians are needed to operate and maintain both furnaces and instruments. Power costs are small in comparison with other expenses, but nevertheless need to be considered. All in all, the total cost of vacuum furnace installation and operation is at present sufficiently high to discourage their use, if other alternatives present themselves.

As to the other objections, rapid methods of leak detection have now been developed, so that what was once a time-consuming task is now a relatively easy one and the introduction to and removal from vacuum furnaces of work *in vacuo* is not an insuperable problem in design. In this connection the possibilities of combining vacuum and controlled atmosphere arrangements in one and the same furnace should not be overlooked.

A practical design for a low-cost furnace, simple in operation and adaptable, if necessary, to large scale production, should incorporate the following features:—

(1) Large volume of work space,
(2) High ratio of work space to furnace space,
(3) Rapid pump-down to the desired range of working pressures—10^{-4} mm. of mercury,
(4) Operating temperatures up to at least 1500°C.,
(5) Provision for rapid entry and removal of work,
(6) Automatic devices for control of furnace (1) to ensure constant operation and (2) to minimize troubles resulting from breakdown.

High-speed diffusion pumps, having capacities of 7000 liters per sec. and over, are now available. These ensure rapid pump-down and low working pressures. Newly developed silicone pump fluids (2) that can withstand atmospheric pressure while hot without appreciable chemical breakdown have been said to provide long periods of trouble-free operation.

The design of the furnace affects both the required pumping capacity and the heat losses. High thermal efficiency demands large volumes of refractories for insulation. Refractories in a vacuum furnace present a serious degassing problem. The logical solution of this problem would seem to be to separate from the high vacuum chamber of the furnace such materials as degas excessively and thereby reduce to a minimum the required pumping capacity. There are two variables involved here, one being the amount of refractory incorporated into the furnace and the other being the capacity of the pumping system. Obviously, the most economical combination has the maximum amount of refractory and minimum pumping capacity. Such a system would, however, require extended time for evacuation and necessitate an extremely low leak rate to maintain a high vacuum. There is probably an optimum combination of the amount of refractory used and the pumping capacity which will satisfy both thermal efficiency requirements and still allow satisfactory evacuation conditions with reasonably small pumps.

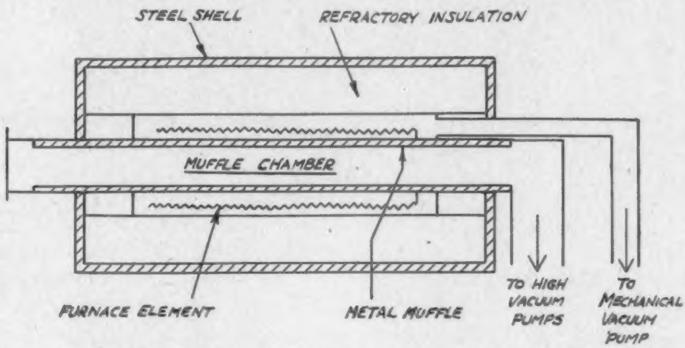

FIG. 1. *Vacuum furnace design employing heat resistant alloy muffle inside insulated heating chamber.*

Two ways of separating the materials which degas from the high vacuum chamber of the furnace may be suggested. On the one hand, one may employ a heat resistant alloy or metal muffle inside an insulated heating chamber as in Fig. 1. On the other hand one may reduce degassing refractories to a minimum and enclose those in the immediate vicinity of the element in a vacuum-tight container made of heat-resistant alloy or metal. In any case a radiation shield is essential if heating of the furnace shell is to be avoided. A furnace of this design is illustrated diagrammatically in Fig. 2.

The first design (Fig. 1) suffers from the disadvantage that the maximum safe operating temperature for long life—say 800°C.—is limited by the creep

resistance of the alloy muffle. Furthermore, at temperatures above 500°C., two pumping systems are needed to avoid collapse of the muffle, one to maintain a high vacuum within the muffle and the other to maintain a vacuum outside the muffle. Operation of the furnace becomes complicated when two pumps are employed. Furthermore, additional control instruments are called for. The chief advantage of this design lies in the almost complete elimination of the degassing problem. Care must be taken in the choice of materials, e.g., chromium may volatilize at working temperatures and contaminate both the heating element and the work. The replacement of muffles is expensive, especially in larger furnaces of this type.

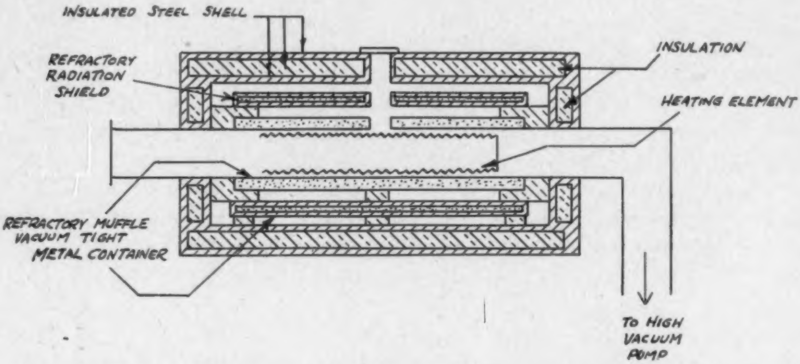

FIG. 2. *Vacuum furnace design in which degassing refractories are enclosed in vacuum tight container made of heat resistant alloy (radiation shield is essential in this design).*

The second design avoids most of the disadvantages of the first. The problem of attaining operating temperatures of 1500°C. and over presents little difficulty. Only one pumping system is needed. Construction and operation are thereby simplified, with savings in both instrumentation and operation. Refractory muffles have a long life and are relatively cheap. Maintenance costs are materially reduced. This design also has potentialities in the construction of large furnaces which will permit production at lower unit cost. But it has the shortcomings of a large metal surface and degassing refractories. However, by attention to details in the design, proper selection of refractories, and by the use of relatively high speed pumps, these shortcomings can be mastered. It should be possible to build industrial furnaces more cheaply to the latter design than the former.

Description of Furnace

The furnace which we are about to describe was built substantially to the design shown in Fig. 2. However, the refractories surrounding the muffle were not enclosed in a metal casing. But for this, the construction would have followed Fig. 2 quite closely.

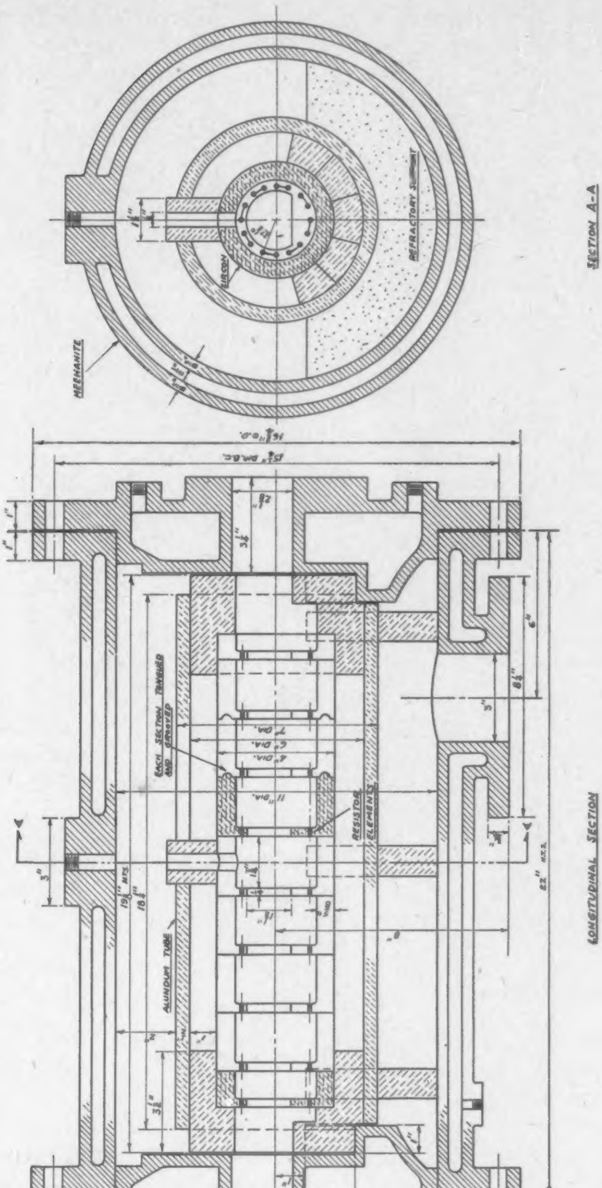

FIG. 3. *Longitudinal section of high vacuum furnace described in paper.*

A fairly detailed drawing, showing the main features of the furnace, is reproduced in Fig. 3.

The furnace shell consists of a tinned cast iron water-jacketed cylinder (see Fig. 4) and two tinned cast iron water-cooled end covers, one of which is shown in Fig. 5. These have proved to be satisfactory, though both cylinder and covers could just as well have been made of steel (welded). When the furnace is in use the covers are bolted to the shell. When the covers were first used, the circular serrations thereon (see Fig. 5) were pressed into lead gaskets (see Figs. 4 and 9) fitted into both ends of the shell. This served to seal the furnace. The rear cover was permanently attached to the shell. Through the opening in it, communication was maintained between the furnace chamber and the pumping system. The front cover (see Fig. 5) was removed only when refractories or windings needed replacement. To the opening in the front cover was secured a small cylindrical chamber which itself was provided with a cover. This light cover, or door, was removed whenever the furnace was to be charged or discharged; it was closed tightly while the furnace was in operation. It was provided with a sight-hole through which the interior of the furnace could be viewed and with small openings through which thermocouple wires could be pushed into or taken from the furnace.

So long as the lead gaskets were used, the lowest pressures which could be obtained in the furnace were of the order of 10^{-3} to 10^{-4} mm. of mercury. The lead gaskets were, therefore, replaced by circular 1/4 in. thick Neoprene gaskets which covered parts of the flat annular areas between the inner circular edges of the lead gaskets and the circular lines of intersection between the flanges and the inner cylindrical surface of the furnace body (see Fig. 4). Reference to Figs. 3 and 5 should make it clear that these Neoprene gaskets were protected from the heat of the furnace by the cooling chambers on the furnace covers which projected somewhat into the interior of the furnace body. Neoprene gaskets were used to seal all other joints in the furnace. The substitution of Neoprene for lead has enabled pressures as low as 0.06μ to be obtained and held without any difficulty whatsoever.

The muffle,* the design of which was suggested in a paper by L. Navias (8), *the radiation shield* (alundum tube), supports and *endpieces* (all of zircon) can be distinguished in Fig. 3.

The *muffle* (Fig. 3), which also supports the resistor elements, is composed of four quadrants—made of zircon tongued and grooved on four sides, so that, when they are fitted together, they form a relatively stable tube. One of these quadrants can be seen on the extreme right in Fig. 6. Four narrow quadrants, fitted together to form a relatively thin ring, are shown alongside the single quadrant on the right of Fig. 6. One such thin ring serves as the endpiece of the muffle when it is assembled (see Fig. 3). The muffle is built up of two

**The zircon refractory parts used in the construction of this furnace were manufactured by the Titanium Alloy Manufacturing Division, National Lead Corporation.*

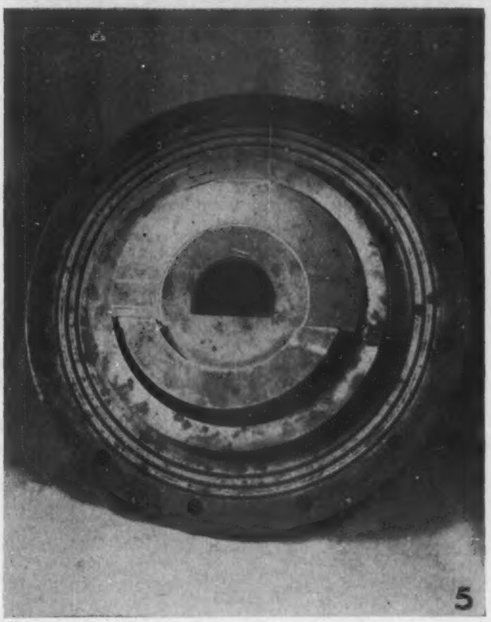

FIG. 4. *Photograph of cast iron furnace shell, showing zircon saddles used to support radiation shield.*

FIG. 5. *Water cooled end cover for vacuum furnace.*

halves, each half consisting of seven pairs of quadrants and one pair of end sections—the latter, when the muffle is assembled, forming the thin ring referred to above. The two halves of the muffle can be seen in Fig. 7, which shows also the way in which the pairs of quadrants and endpieces are fitted together. The heating elements, of which there are two, are threaded through the holes in the quadrants and endpieces. The upper half of the muffle is provided with

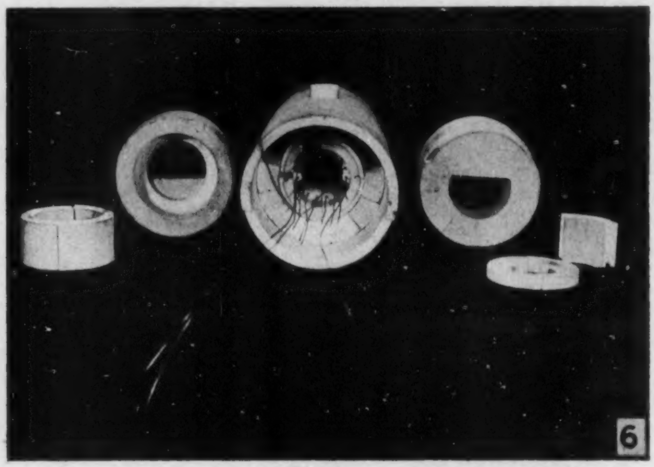

FIG. 6. *Parts of vacuum furnace muffle; assembled (center of photograph); disassembled (both sides of center).*

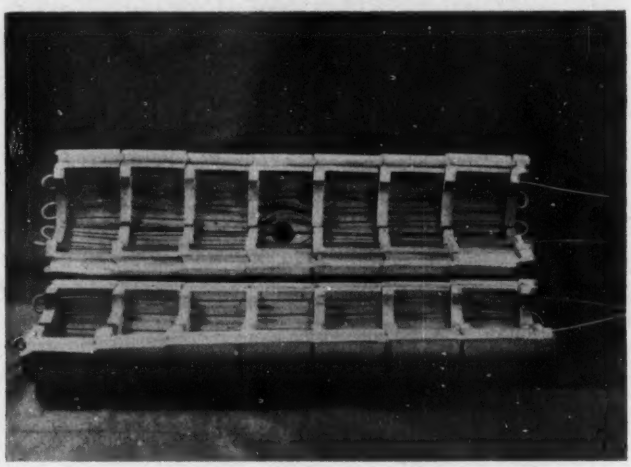

FIG. 7. *Photograph showing resistor elements supported on zircon quadrants—note tongued and grooved connections between the quadrants.*

a hole (see Figs. 3, 7, and 8), through which the contents of the furnace can be sighted from outside the shell. This hole is aligned with holes in the radiation shield and in the top of the furnace shell (see Fig. 3).

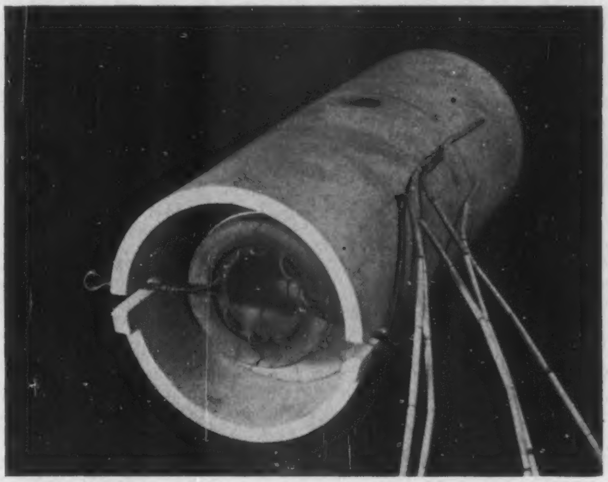

FIG. 8. *Photograph of muffle showing ends of heating elements and method of connecting them to power leads. This also shows method of introducing thermocouples into furnace.*

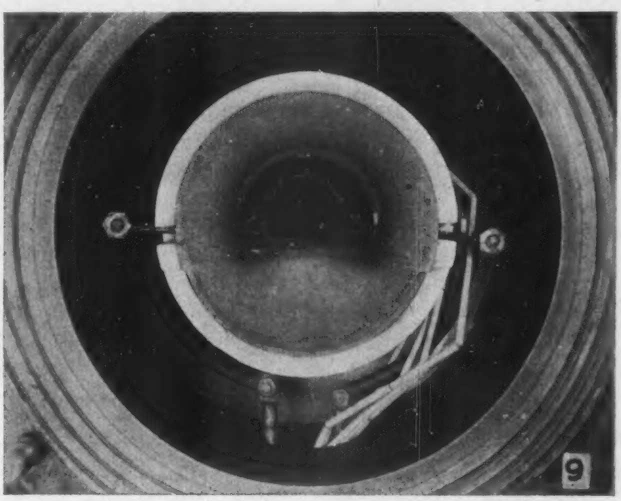

FIG. 9. *Photograph showing muffle assembled in furnace shell. Zircon saddles can be dimly seen under radiation shield.*

The muffle and the radiation shield are concentric. The muffle rests within the shield upon a saddle consisting of a number of segments (section *A-A* in Fig. 3) and two end supports (Fig. 3). These were made of a zircon grog mixture. The shield is a standard 6 in. I.D. alundum tube. The relative positions of the muffle, the supporting segments, and the shield when they are about ready for insertion in the furnace shell will be gathered by reference to Figs. 8 and 9. In these pictures only the end supports are missing from the assembly. In Fig. 6 the two end supports are shown, one on either side of the muffle-shield assembly. Fig. 8 is of value in showing how the heating elements are located in and brought together at the ends of the muffle. Thermocouples which were at one time used for measuring temperatures at various points in the shield and muffle are also shown in this figure.

During the assembly of the muffle the wires forming the heating elements serve to hold all the quadrants together. The elements first used consisted of 0.06 in. diameter molybdenum wire. Heavier wire—0.08 in. diameter—has later been employed for the purpose of increasing the life of the elements. The elements are arranged in series–parallel.

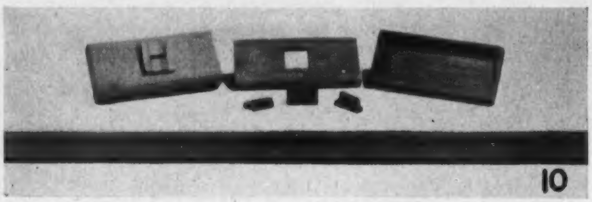

FIG. 10. *Graphite hearth and specimen box.*

The ends of the radiation shield rest on water cooled supports which form part of the furnace covers. The support on the front cover can be seen in Fig. 5. To prevent sagging of the shield between these supports three zircon saddles about 1 in. wide are provided. These are placed at about equal distances from one another and from the cover supports. One of the zircon saddles can be seen dimly in Fig. 9, which shows the assembled parts in place in the furnace shell, together with the furnace leads and thermocouples entering a hole in the bottom of the shell. This hole is provided with a cover so designed that the necessary connections between the leads and thermocouples and the power supply, instruments, etc., can be made without affecting the vacuum in the shell.

When the parts are assembled as in Fig. 9, it remains only to bolt the front cover to the shell to put the furnace in shape for use. It is ordinarily possible for an experienced man to rewire a burnt-out element within an eight-hour day.

The muffle shown in Fig. 9 and the opening in the front cover shown in Fig. 5 line up with each other, so that a thin strip of graphite (see Fig. 10) can be slid into the muffle to form its hearth. The hearth is grooved along its entire

length. Boxes with covers made of graphite—the former provided with tongues which fit the groove in the hearth—are used to contain such things as are to be heated to high temperatures *in vacuo*. In the covers, holes are provided into which can be fitted targets against which an optical pyrometer, for checking temperatures, or a Rayotube, for controlling temperatures, can be sighted. The graphite hearths have caused no trouble in contact with the zircon refractories at temperatures up to 1300°C. Recent work (7) confirms our experience and indicates that the oxides ZrO_2, CaO, BeO, MgO, Al_2O_3, and ThO_2 may be used in contact with carbon in the range of temperatures up to 1300°C. before appreciable reaction occurs.

Vacuum System

Pressures of the order of 10^{-3} to 5×10^{-5} mm. of mercury are obtained in the furnace chamber by using an oil diffusion pump (275 liters per sec.) backed by a mechanical vacuum pump (5 liters per sec.) operating against a leak rate estimated at about 0.0004 liters per hr.

Most of the small vacuum lines are made of copper tubing of standard size. Standard size compression seals are used where necessary to facilitate the installation of gauges, discharge tubes, auxiliary equipment, etc. The power consumption of the vacuum apparatus and instruments amounts to about 0.9 kw.

The operating pressure is reached within 20 min. after starting the pumps.

Power Supply

Power is supplied to the furnace in 2 v. steps by a 25 cycle, 5 kw. step-down transformer. The power demand of the heater elements at 1300°C. is approximately 3.9 kw. at 46 v. Although high voltages sometimes cause ionization of gases, resulting in short circuiting of the heaters, difficulty due to this has not been encountered in our equipment. During certain periods of gas evolution glow discharge has been noted, but this is almost always of short duration.

Temperature Measurement and Control

Since measurement and control of temperature were important in the work for which the furnace was designed, provision was made for:

1. Automatic recording and control of temperatures,
2. Calibration of the work temperature with an automatic control unit,
3. Means of checking the work temperature periodically.

Automatic recording and control of the temperatures in the furnace are achieved by means of Leeds and Northrup automatic control equipment connected to a radiation type pyrometer (Rayotube). The pyrometer, adjusted for a lens-to-target distance of 12 in., is sighted through a quartz glass window on to the graphite target fitted into the cover of the specimen box. Because

of the small heat capacity of the heater the time–temperature response is fast on cooling, but slow as the temperature approaches the operating temperature.

As this characteristic of the furnace might result in a large on–off variation in the temperature only a small percentage of the power input is controlled. This is done by shunting in and out of the heater circuit a resistor in parallel with it.

A platinum–platinum–rhodium thermocouple, protected throughout its length, can be placed either inside the specimen box or fastened to the work for checking the temperature of work as recorded by the optical pyrometer or the Rayotube. It has been our practice to calibrate the optical pyrometer and Rayotube after all major shut downs for repairs or rewiring of heating elements.

The temperature of the work is checked periodically by means of an optical pyrometer which is mounted above the furnace in such a way that it can be swung over the quartz window at a moment's notice. During the time that the optical pyrometer is in use, the Rayotube is pushed to one side. The times occupied in making check observations of temperatures are so short as to be negligible in their effect on the operation of the furnace. The thermocouples which are sometimes attached to the refractories to determine the temperature gradients in the furnace provide additional means of checking temperatures.

In general, temperatures can be controlled within $\pm$ 10°C. and, with very careful adjustment and calibration, it should be possible to control them within $\pm$ 5°C.

Controls and Protective Devices

It was necessary to provide a certain measure of automatic control for two reasons: (1) to obtain reasonably consistent time–temperature and time–pressure cycles from run to run, and (2) to enable the worker to use his time in other tasks while the furnace was operating.

The diagram in Fig. 11 shows the arrangement of the control system. The various parts are referred to by number in the diagram and are described in numerical order below:

(1) Switch for starting the mechanical pump and the cooling system simultaneously. The cooling system supplies water to the furnace and cover jackets, to the diffusion pump, to the water-cooled leads and to the baffles.

(2) On–off switch for manually energizing the solenoid oil valve on the mechanical pump.

(3) On–off switch for energizing the heater of the diffusion pump.

(4) Variable tap transformer for controlling the power input to the furnace. The automatic temperature control system has not been indicated on this diagram.

(5) Switch for turning on automatic pressure control unit. A Pirani gauge is used in combination with a sensitive d-c. switch and electronic relay to shut off and turn on automatically the heater of the diffusion pump when the pressure in the furnace vacuum chamber rises or falls past a preset level. When the heater is turned off, a solenoid valve is energized and directs water to the cooling coils of the heater, and vice versa.

(6) Time clock which may be preset to turn off the vacuum pumps automatically. The sequence numbers on the arrows indicate that the heater of the diffusion pump is first turned off. After a short period of time to allow for cooling of the oil the clock actuates a relay which simultaneously de-energizes a solenoid valve closing off the supply of oil to the mechanical pump and cuts off the main water supply to the equipment.

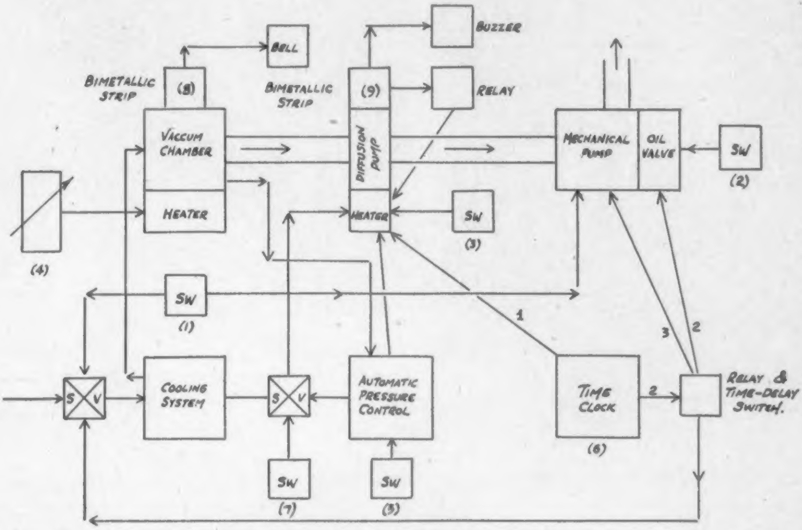

FIG. 11. *Diagram of vacuum system and electric controls for high temperature vacuum furnace.*

(7) On–off control switch for solenoid valve controlling cooling water to heater.

(8) Bimetallic strip type regulator which rings an alarm bell and by means of a relay cuts off the power to the furnace should the water supply fail when the furnace is operating.

(9) Bimetallic strip type regulator which protects the oil diffusion pump from overheating due to failure in the supply of cooling water. The bimetallic strip actuates a buzzer and a relay for turning off the power to the heater.

Operational Characteristics

Heater Life

Element failures have been recorded and examined and sections of weakness have been investigated. The record of element failures given in Table I shows an increase in the life of the element from 50 to 229 hr. for a 0.060 in. diameter molybdenum wire. This increase in wire life resulted from observations of the points in the wires where failure occurred. Where sections of weakness in the elements were detected, they were reinforced by winding round them coils of molybdenum wire in the manner shown in Figs. 7, 8 and 9. Failures were found to occur wherever the wire had been strained in forming the elements; e.g., at the 180 degree hair-pin turns, and at the slight bends in the elements near the sight-hole (see Fig. 7). The last failure recorded in Table I (series *F*) occurred in a straight and presumably unstrained portion of wire near the end of the furnace remote from the diffusion pump.

TABLE I

Series	No. of runs	Hours at temperature	Total operating time, hr.	Diameter of wire, in.			Location of failures	Remarks
				Pump end	Center	Entrance end		
A	13	50	138	0.048	0.056	0.050	At hair pin turn	
B	22	90	244	0.056	0.056	0.049	At entrance end	Hair pin turns reinforced
C	41	203½	485	0.051	0.055	0.053	Bend adjacent sight hole	Hair pin turns reinforced
D	39	185	428	0.057	0.055	0.053	" "	" "
E	39	188	432	0.057	0.056	0.049	" "	" "
F	50	229	538	0.054	0.048	0.043	Entrance end	Bend at sight hole reinforced
Total	204	945½	2272					
			Average	0.054	0.054	0.049		

Note: The majority of the runs were made at a temperature of 1300°C. and at a pressure of 5×10^{-3} *to* 10^{-3} *mm. of mercury.*

Measurements of the diameter of the wire taken at various points along the elements are given in Table I. It was noted that the diameter was least at that part of the heater farthest from the pump end of the furnace. It was noted also that a dark gray sooty deposit of scale decreasing in amount toward the pump end tended to form on the inside surface of the zirconia refractory muffle. Spectrographic analysis of the scale showed that molybdenum was its major constituent—it was probably in the form of oxide. There were traces of other impurities, but nothing to suggest pickup of materials from the refractories. It was surmized from these observations that the failures were caused by the formation of molybdenum oxide and subsequent vaporization of the oxide, followed by condensation of the vapor on the refractories. The more rapid deterioration of the winding at the fore-end of the furnace may be explained in part by the lower total gas pressure at the pump end of the furnace and in part by the reducing action of hydrogen gas evolved from the materials

(hydrides) that were treated in the furnace. It is thought that the hydrogen which swept over that part of the element extending from the center of the element to the pump opening gave some measure of protection from oxidation.

Our experience to date suggests that the life of elements might be prolonged (1) by reinforcing weak portions of the winding in the manner described above, (2) by using heavier wire, and (3) by using lower pressures. A slow leak of hydrogen into the furnace might also be useful in prolonging element life.

When forming bends in wire greater than 0.080 in. it was found difficult to avoid splitting or breaking, even when the wire had been brought to red heat. Stranded wire, having greater flexibility, is recommended for heavier windings. Experience has shown that stranded molybdenum windings operating in hydrogen have longer life than single strand wire of equivalent cross-sectional area. Whether this is true of molybdenum windings operating *in vacuo* remains to be proved.

The zircon muffle has shown little evidence of cracking or spalling. Even the alundum tube, which was found to have cracked the first time the furnace was dismantled, can still be used and looks as though it may be used many times over yet.

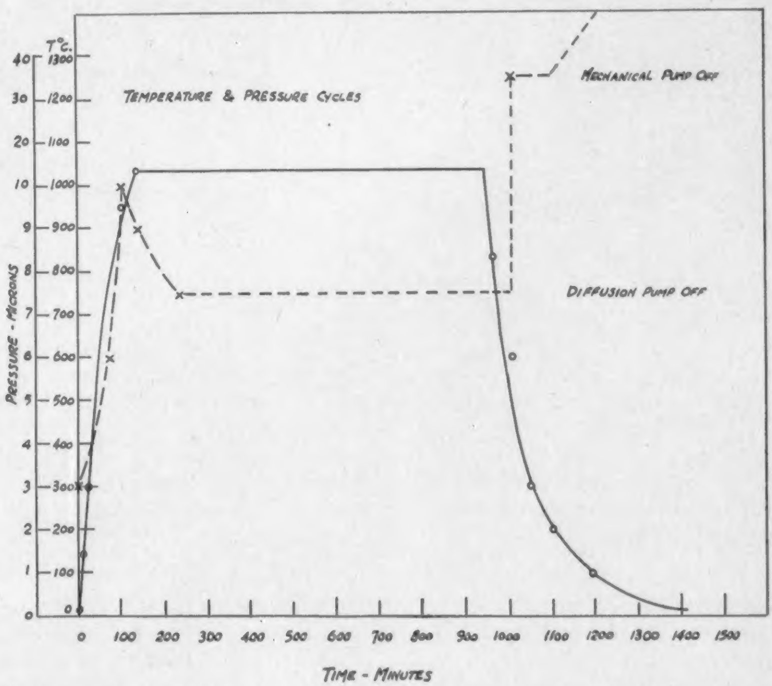

FIG. 12. *Time–temperature and time–pressure curves of typical run in vacuum furnace at 1035°C.*

Energy Requirements, Heating and Cooling Characteristics

The operation of the furnace may be judged by reference to the time–temperature and time–pressure curves of a typical early run at 1035°C., shown in Fig. 12. Heating and cooling curves are shown in Fig. 13. Since it is useful to know the energy required to reach the control temperature for various heating-up times, the curves in Fig. 14 were plotted from the data contained in Fig. 13. Upon reaching the control temperature the rate of energy input gradually decreases as the furnace refractories heat up, until it attains the final value for the steady-state energy loss.

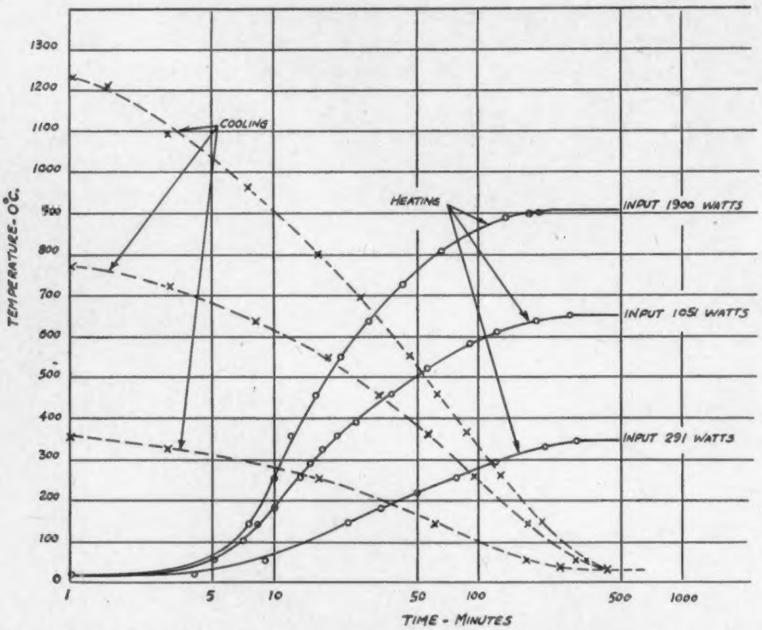

FIG. 13. *Curve showing times of heating vacuum furnace to various control temperatures at various inputs of energy.*

The relation (see graph in Fig. 15) between steady-state energy loss and temperature in absolute degrees may be expressed by an empirical formula of the parabolic type

$$E = KT^n,$$

where E is the energy in watts, T the temperature in absolute degrees, K a constant, and n the slope of the curve as measured on linear co-ordinates. There are many ways in which this relation might be expressed. In this case, however, the parabolic function has been chosen, because it is more likely to have some basis in the Boltzman expression for transfer of energy by radiation.

The calibration curves for temperature and energy input of carbon resistor furnaces obey this same relation (1, 3). The constant K may be regarded as an over-all thermal resistivity coefficient, the value of which, for cylindrical heaters of the type herein described, will depend largely upon the shape factor

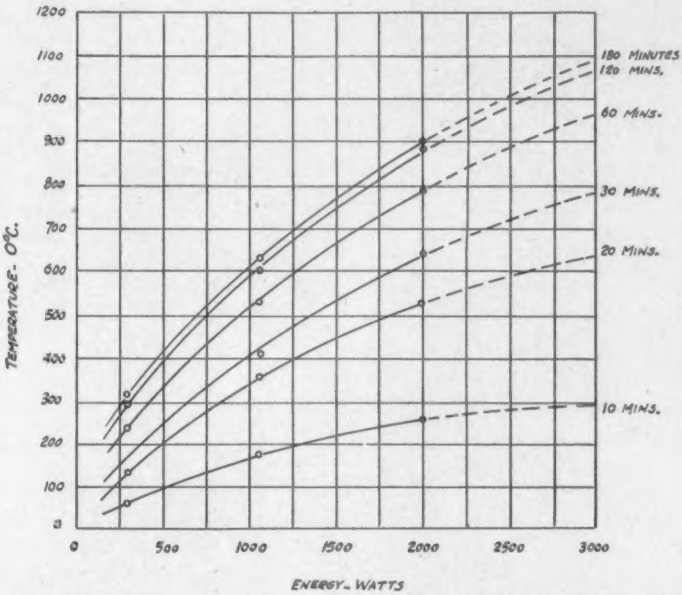

FIG. 14. *Relation between energy input and temperature in terms of various heating times.*

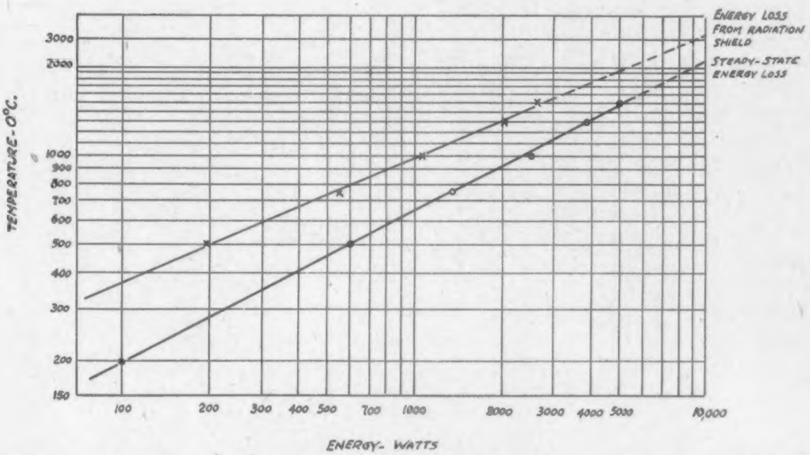

FIG. 15. *Relation between steady state energy loss and temperature in absolute degrees for vacuum furnace.*

of both the heater and the radiation shield. The value of n is constant for a given furnace and seems to vary with different furnaces from 2 to 4. Table II gives the equation for several furnaces described in the literature.

TABLE II

Furnace type	$E = KT^n$	Remarks
Evans (3)	$1750 \times 10^{-6}T^{2.0}$	Carbon resistor
Kroll (6)	$400 \times 10^{-6}T^{2.1}$	Molybdenum wound
Arsem (1)	$51.4 \times 10^{-6}T^{2.3}$	Carbon resistor
Kuhn and Ellis	$7.1 \times 10^{-6}T^{2.74}$	Molybdenum wound
Kroll (6)	$1.3 \times 10^{-6}T^{3.03}$	" "
Kroll (6)	$0.003 \times 10^{-6}T^{3.85}$	" "

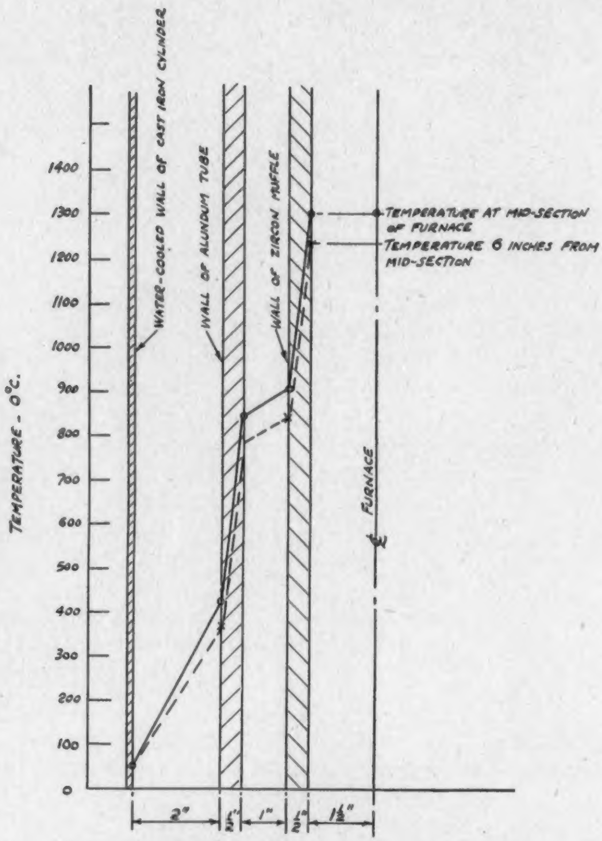

FIG. 16. *Schematic representation of temperature gradients in various parts of vacuum furnace.*

Table II shows that, in general, K tends to get smaller as n approaches 4. The thermal resistance of the above furnaces was roughly estimated to follow the numerical order given in the table. Also, those furnaces having small values of K and high value of n had the least thermal efficiency.

The area-to-volume ratio of cyclindrical shapes decreases with increasing shape factor, the wall thickness remaining constant. It follows then that the heat energy required to maintain a unit volume of useful furnace space at a given temperature will be less for larger furnaces.

Observations of temperature were made by means of thermocouples situated at the mid-section and 6 in. from the mid-section just below the surface, and at points on the outer diameter of the muffle (zircon) and on the inner and outer diameter of the radiation shield (alundum). The temperature gradients for the above locations shown schematically in Fig. 16 make clear the advantage of the additional insulation afforded by the use of an inside winding.

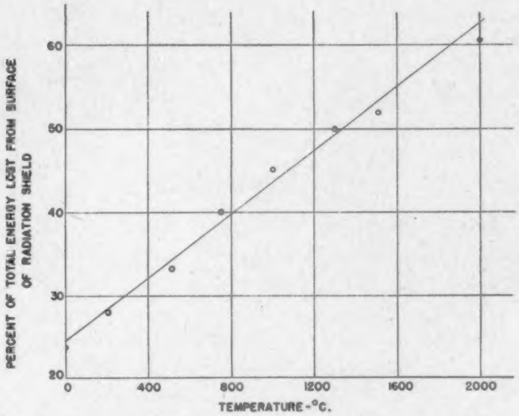

FIG. 17. *Relation between total heat input dissipated from surface of the alundum shield in vacuum furnace and furnace temperature.*

Calculations were made of the approximate heat transfer from the outside surface of the alundum radiation shield to the walls of the iron cylinder. A graph showing the relation between heat transfer (approximate) and furnace temperature is shown in Fig. 16. The percentage of the total heat input dissipated from the surface of the alundum shield was also calculated and is shown plotted against furnace temperature in Fig. 17. The difference between the energy input and that dissipated from the surface of the alundum tube is attributed to radiation and conduction losses through both ends of the heater. There is a much smaller loss through the supports beneath the alundum tube and in the transformer. Radiation losses from the shield are greater at the higher temperatures, as might be expected. The steady-state energy requirements for a given temperature may be reduced appreciably by increasing the

effectiveness of the radiation shield. At the same time the end losses will appear proportionately larger. It is to be noted that end losses become less significant the longer the furnace. For this reason the thermal efficiency of long furnaces will depend largely upon the effectiveness of the radiation shield.

Radiation Shield Requirements

The requirements of an effective radiation shield are:

1. Strength at high temperature sufficient to resist slow buckling and sagging over a long period,
2. High thermal resistance,
3. Long life.

It is suggested that the above requirements can be obtained by careful design from such readily available materials as stainless steels for the casing and granular alumina for insulation. Since the creep strength of stainless steels is of a low order, it may be necessary to use chaplets to separate the walls of the casing and refractory supports to prevent the shield from sagging on to the muffle. Longitudinal corrugations along the casing may provide additional support. Oxidation resistance is not essential, though it is desirable, especially if the furnace is to be opened to the atmosphere.

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